

# VERY HIGH ENERGY GAMMA RAYS FROM THE VELA PULSAR/NEBULA

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## ABSTRACT

We have observed the Vela pulsar region at TeV energies using the 3.8 m imaging Čerenkov telescope near Woomera, South Australia every year since 1992. This is the first concerted search for pulsed and unpulsed emission from the Vela region, and the imaging technique also allows the location of the emission within the field of view to be examined. A significant excess of gamma-ray-like events is found offset from the Vela pulsar to the southeast by about  $0^\circ.13$ . The excess shows the behavior expected of gamma-ray images when the asymmetry cut is applied to the data. There is no evidence for the emission being modulated with the pulsar period – in contrast to earlier claims of signals from the Vela pulsar direction.

## INTRODUCTION

The Vela pulsar, PSR B0833 – 45, is an 89 msec pulsar and the brightest 100 MeV gamma-ray pulsar. The Crab pulsar and PSR B1706 – 44 are also strong 100 MeV gamma-ray sources, and both have been detected as very high energy (VHE) gamma-ray sources (e.g. Weekes et al., 1989; Tanimori et al., 1994; Kifune et al., 1995). The emission from these VHE sources is apparently unpulsed and the acceleration site for the progenitor electrons is probably the shock generated by the pulsar wind colliding with circumstellar matter. There have been some claims<sup>1</sup> for pulsed VHE emission from the Vela pulsar (Grindlay et al., 1975; Bhat et al., 1987). However, with the exception of a short subset of Grindlay et al.’s data, only pulsed emission has been searched for in the previous VHE observations, and unpulsed gamma rays are likely emitted also from the Vela pulsar/nebula owing to a mechanism presumably similar as the Crab pulsar/nebula. The atmospheric Čerenkov imaging technique has made possible the search for

<sup>1</sup>Their results were not confirmed by later observations (see Edwards et al., 1994).

unpulsed VHE gamma rays, and the CANGAROO 3.8 m telescope (Hara et al., 1993) is used for the first attempt of searching for unpulsed VHE emission from the Vela pulsar/nebula.

We have observed the Vela pulsar region by the CANGAROO 3.8 m telescope every year since 1992 and usable data were obtained in 1993, 1994, 1995 and 1997. The on-source data from 1993 to 1995 amount to about 174 hours in total, of which about 119 hours data remain after rejecting the data affected by clouds. Almost the same amount of off-source data has been taken night by night. The 3.8 m mirror was recoated in October 1996 and the reflectivity was improved from  $\sim 45\%$  to  $\sim 90\%$  at 480 nm (Wild et al., 1995). The 1997 data are still under analysis. Only the 1993 to 1995 data are used in the following analyses.

## ANALYSES AND RESULTS

The analysis method is based on parameterization of the shape, location and orientation of Čerenkov images detected by an imaging camera (Hillas, 1985; Reynolds et al., 1993). The gamma-ray selection criteria in the present analysis are determined by Monte Carlo simulations to be  $0^\circ.01 < \text{width} < 0^\circ.09$ ,  $0^\circ.1 < \text{length} < 0^\circ.4$ ,  $0.3 < \text{conc}$ ,  $0^\circ.7 < \text{distance} < 1^\circ.2$  and  $\alpha < 10^\circ$ . The simulations show that more than 99 % of background events are rejected after the above selections are made, while  $\sim 50\%$  of gamma-ray images from a point source remain.

First, we searched for a gamma-ray signal from the pulsar position and found a significant excess of on-source events above the background (off-source) level. However, the peak profile of the excess distribution against  $\alpha$  was broader than expected from a point source. Next, gamma-ray emission was scanned from other positions than the pulsar position. The position of the maximum excess counts was found to be offset from the pulsar by about  $0^\circ.13$ . Figure 1 shows the  $\alpha$  distributions of the events from the position of the maximum excess counts after the other selection criteria have been applied. The statistical significance of the excess after including the selection of  $\alpha$  is at the  $5.2\sigma$  level.

In the usual image analysis, the image parameters are calculated assuming gamma-ray images to have a simple elliptical shape. Gamma-ray images, however, are asymmetrical along their major axes, having an elongated, comet-like shape with the “tail” pointing away from the source position. This feature can be characterized and quantified by another image parameter called the “asymmetry” (Punch, 1993). From Monte Carlo simulations, about 80 % of gamma-ray images have positive values of “asymmetry”, while the distribution of background images is almost symmetrical because of their isotropic arrival directions in the field of view (Yoshikoshi et al., 1997). The asymmetry parameter was calculated assuming that the source lies at the position of the maximum excess counts, to examine the gamma-ray-like feature of the excess events. The asymmetry distribution of the excess events was found to be asymmetrical with the peak on the positive side as expected from the simulation. This result gives clear corroborative evidence that the detected excess events of Figure 1 are truly due to gamma rays. The significance of  $5.2\sigma$  for the excess counts in the  $\alpha$  distribution of Figure 1 increases to  $5.8\sigma$  by adding asymmetry  $> 0$  to the gamma-ray selection criteria.

As an alternative method to calculating the  $\alpha$  parameter, it is possible to infer and assign the true direction of a gamma ray from the location and orientation of its observed Čerenkov image. We have calculated a probability density for the true direction for each observed gamma-ray image using Monte Carlo simulations (Yoshikoshi, 1996). Thus, a density map of gamma-ray directions can be plotted against right ascension and declination by adding up all of the probability densities of the gamma-ray-like images. The contribution of the gamma-ray source in the field of view can then be found as an event excess in the on-source map over the background (off-source) map. Figure 2 shows the density map of the excess events for the Vela pulsar data plotted as a function of right ascension and declination. The significant

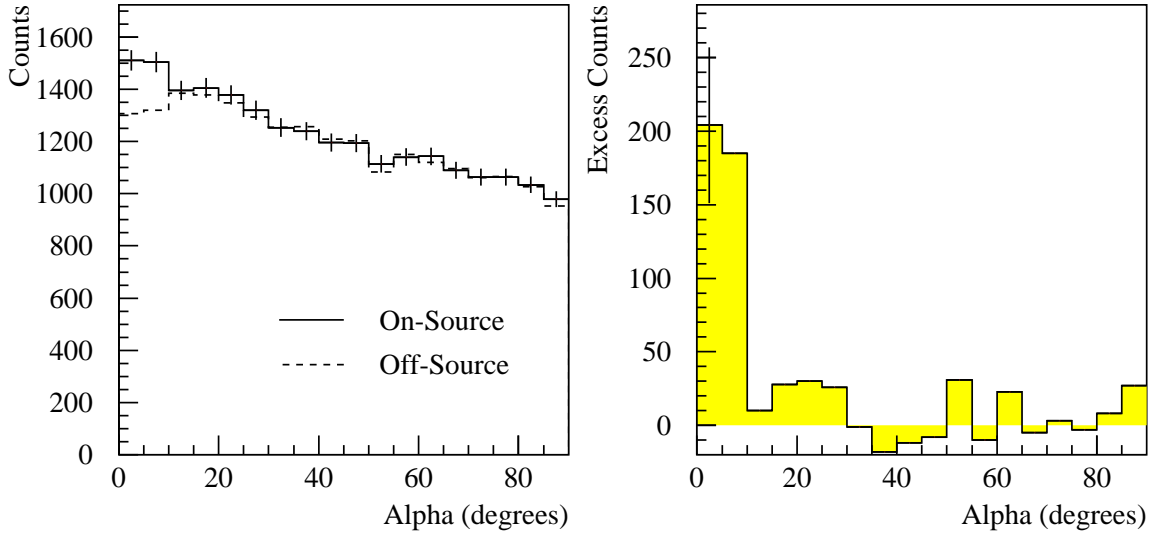


Fig. 1: Alpha distributions of gamma-ray-like events in the direction of the maximum excess counts, which is offset by about  $0^\circ.13$  to the southeast from the Vela pulsar, and corresponds to the peak position in Figure 2. The on-source and off-source distributions are shown in the left. The excess counts of the on-source above the background (off-source) level are plotted in the right.

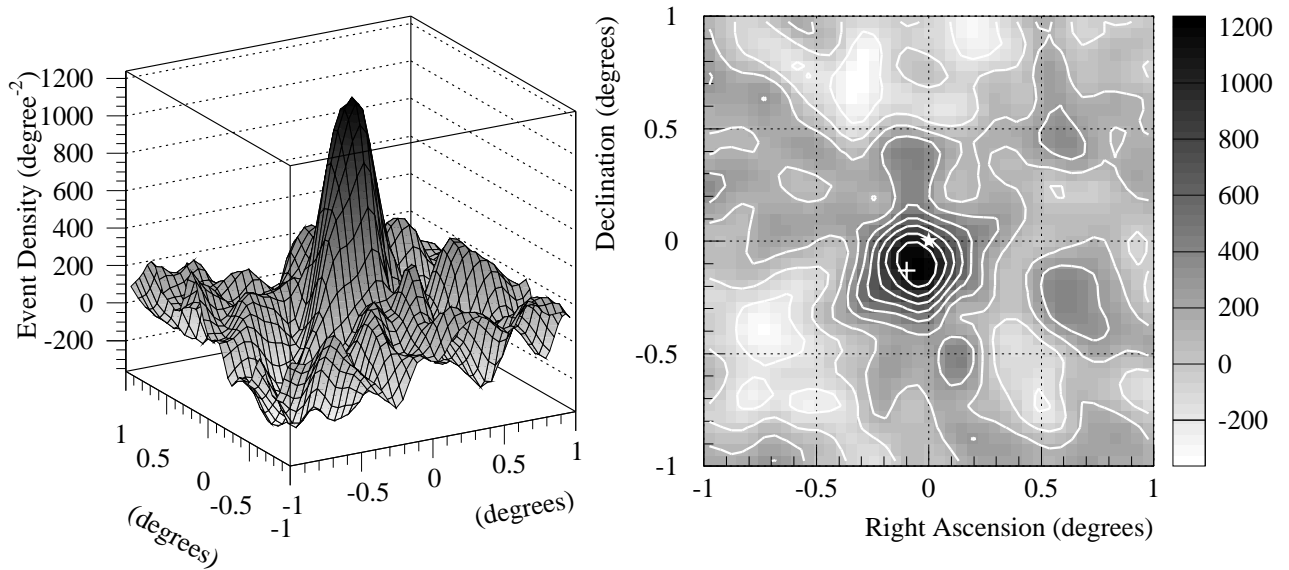


Fig. 2: A density map of excess counts around the Vela pulsar plotted as a function of right ascension and declination. North is up and east is to the left in the contour map, and the gray scale at the right is in counts  $\text{degree}^{-2}$ . The “star” at the origin of the contour map indicates the position of the Vela pulsar. The position of the maximum excess counts from the 1997 data is indicated by the “cross”.

excess due to a gamma-ray source near the pulsar exists in this map. The position of maximum emission is offset from the pulsar, which is indicated by the “star” mark in the contour map, to a position southeast by about  $0^\circ.13$ . The alpha distribution of Figure 1 is plotted for the position of maximum emission. We have found a gamma-ray-like event excess also from the 1997 data with a significance of more than  $4\sigma$  and the position of maximum excess counts, indicated by the “cross” in Figure 2, agrees with that from the 1993 to 1995 data within the statistical error ( $\sim 0^\circ.04$ ).

The gamma-ray integral flux calculated for the position of the maximum excess counts is  $(2.9 \pm 0.5 \pm 0.4) \times 10^{-12}$  photons  $\text{cm}^{-2} \text{sec}^{-1}$  above 2.5 TeV, where the first and second errors are statistical and systematic respectively. The threshold energy, which we defined as the energy of the maximum differential flux of detected gamma-ray-like events, has been estimated from Monte Carlo simulations to be 2.5 TeV, assuming a power law spectrum with a photon index of  $-2.5$ . The systematic error for this threshold energy is about  $\pm 1.0$  TeV, which is due to uncertainties in the photon index, the trigger conditions and the reflectivity of the mirror. The data have been divided to calculate year-by-year fluxes and the fluxes are consistent with no variation having been detected on the time scale of two years.

The periodicity of the events detected from the Vela pulsar direction and the direction of the maximum excess counts has been investigated using our 1994 and 1995 data for which the GPS receiver was available (Yoshikoshi et al., 1997). No significant value of the  $Z_2^2$  statistic (Buccheri et al., 1983) has been found for either the excess direction nor the pulsar direction.

## CONCLUSION

We have observed the Vela pulsar region with the CANGAROO 3.8 m telescope since 1992 and found a VHE gamma-ray signal from the direction  $0^\circ.13$  offset from the Vela pulsar to the southeast at the  $5.8\sigma$  level in the 1993 to 1995 data. This gamma-ray signal corresponds to the integral flux of  $(2.9 \pm 0.5 \pm 0.4) \times 10^{-12}$  photons  $\text{cm}^{-2} \text{sec}^{-1}$  above 2.5 TeV and is consistent with steady emission over the two years. No pulsed emission modulated with the pulsar period has been detected.

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